WIRELESS COMMUNICATION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority from provisional application Serial No. 60/190,822, filed 03/21/00.

BACKGROUND OF THE INVENTION

The invention relates to electronic devices, and more particularly to wireless communication.

Demand for wireless information services via cell phones personal digital assistants (PDAs), and Internet appliances (IA) plus wireless networking among notebook computers is rapidly growing. Various protocols for wireless communication have been proposed, including the 802.11 standards for wireless networking at high data rates (e.g., 20 Mbps). In particular, Orthogonal Frequency Division Multiplexing (OFDM) has been suggested for the 802.11 wireless local area network 5 GHz band standard. For transmission, OFDM essentially splits a data stream into N parallel substreams with each substream on its own subcarrier (frequency division multiplexing). The subcarriers are taken to be initially orthogonal by frequency selection. Thus the subcarriers may overlap spectrally because the orthogonality allows a receiver to separate them. But channel dispersion disrupts the orthogonality.

OFDM with pilot symbols aided schemes help overcome the sensitivity to frequency offsets between a transmitter and receiver oscillators and Doppler effects. Garcia et al, Joint 2D-Pilot-Symbol-Assisted-Modulation and Decision-Directed Frequency Synchronization Schemes for Coherent OFDM, IEEE ... 2961 (2000)

Lee et al, Antenna Diversity for an OFDM System in a Fading Channel, IEEE Military Comm. Conf. Proc. (MILCOM) 1104 (1999) considers multiple receiver antennas and applies various combining methods for receiving OFDM transmissions.

SUMMARY OF THE INVENTION

The present invention provides a wireless system with orthogonal frequency division multiplexing with two or more transmission antennas and the subcarrier symbols of a burst from one antenna being a transformed version of the subcarrier symbols of the corresponding burst from another antenna.

This has advantages resistance to fading by simple symbol transformations.

BRIEF DESCRIPTION OF THE DRAWINGS

The drawings are heuristic for clarity.

Figure 1 shows a preferred embodiment transmitter.

Figure 2 shows subcarrier structure of a burst.

Figures 3-13 illustrate preferred embodiment subcarrier diversity pairings.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

1. Overview

Preferred embodiment systems provide antenna diversity for orthogonal frequency division multiplexing (OFDM) using pilot-symbol aided frequency synchronization by pairing subcarriers and applying a transformation (e.g., rotation and complex conjugation) to the data (pilot) symbol pair on the subcarrier pair for transmission on a second antenna. Figure 2 shows the subcarrier structure of a transmission burst, and Figures 10-11 illustrates pilot and data symbols and their transformation within a burst and across bursts, respectively. This provides diversity and better performance than just maximal ratio combining of the same data on the same subcarrier from the two antennas. The subcarrier pairing extends to higher order groupings and transformations for larger antenna arrays.

Reception of the transmissions from the multiple antennas utilizes the orthogonal frequency division multiplexing character of the transmissions.

2. Two antennas, adjacent subcarriers preferred embodiments

Figure 1 illustrates a preferred embodiment system which uses a preferred embodiment method of data space-frequency transmission diversity. The first preferred embodiment proceeds as follows with an input data stream.

(1) Optionally apply forward error correction (e.g., Reed-Solomon or turbo coding) to a binary input data stream.

(2) Encode the input data stream (including forward error correction) into QAM symbols (e.g., for 16-QAM the symbols are $z_k = x_k + jy_k$ with x_k and y_k from the set $\{\pm 1, \pm 3\}$).

(3) Interleave the data symbols with the pilot symbols. Partition the QAM symbols into bursts of N symbols so each burst has N_{data} data symbols and N_{pilot} pilot symbols; see Figure 2 heuristically illustrates the interleaved symbols in a burst for the case of every fourth symbol as a pilot symbol. Typical values include N = 64 symbols in a burst consisting of N_{data} = 48 data symbols and N_{pilot}

= 16 pilot symbols. Note that possibly extra 0 power subcarriers may be required at the frequency ends of a burst for regulatory reasons; that is, the highest and lowest frequency subcarriers may have 0 power. In this case $N = N_{data} + N_{pilot} + N_{zeros}$ where N is the size of the IFFT for step (5).

(4) For each burst from step (3) form a transformed burst by changing each pair (a, b) of successive data symbols into the pair $(-b^*, a^*)$. That is, the N_{data} data symbols form $N_{data}/2$ pairs, and for each pair perform the complex conjugation and a $\pi/2$ vector rotation. This creates a transformed burst of symbols made up of the same N_{pilot} pilot symbols but the new $N_{data}/2$ pairs of transformed data symbols. Figure 3 illustrates the two bursts.

(5) Apply an N-point inverse fast Fourier transform (IFFT) to each of the N-subcarrier bursts from steps (3) and (4). The subcarrier number variable k in a burst has the range 0 to N-1 (e.g., 63) and corresponds to frequencies in the range 0 to (N-1)/T where T is the period of a burst, for example 10 microseconds. The inverse transformed time variable has the range 0 to T in increments of T/N. That is IFFT of a burst with symbols $z_0, z_1, \ldots, z_{N-1}$ for t in the range [0,T] is:

$$u(t) = \sum z_k e^{j2\pi kt/T} \quad \text{with the sum over } 0 \leq k \leq N-1$$

(6) Optionally, add a guard interval (cyclic redundancy) to precede the u(t) for each burst from step (5). Then as in Figure 1 use the u(t) for each burst to QPSK modulate an intermediate frequency carrier followed by step up of frequency to the 2.5 or 5 GHz carrier center frequency. Transmit each burst modulated carrier on a corresponding antenna. Alternatively, the u(t) for each burst can directly modulate the carrier.

The reception of the transmitted signal from transmitter step (6) includes the following steps.

(1) Demodulated and apply FFT to recover for each burst subcarrier a linear combination of the symbols transmitted by the two antennas for the subcarrier. That is, for the subcarrier from transmitter steps (3)-(4) with transmitted symbols a and $-b^*$, the received signal is $r_1 = \alpha a + \beta(-b^*) + n_1$ where α is the attenuation plus phase shift of the channel from the first antenna to the receiver, β is the attenuation plus phase shift of the channel from the

second antenna to the receiver, and n_1 is the received noise in this subcarrier. Similarly, for the adjacent subcarrier with transmitted symbols b and a* the received signal is $r_2 = \alpha\, b + \beta\, a^* + n_2$.

(2) Use the pilot symbols to estimate the channel parameters. For example, find estimates $\alpha^\wedge$ and $\beta^\wedge$ from the (known) received pilot symbols in the pilot symbol subcarriers closest to the subcarriers with data symbols a and b; or apply an interpolate method using channel estimates from pilot symbols of subcarriers above and below the subcarrier of interest. Then find estimates $a^\wedge$ and $b^\wedge$ for the data symbols a and b in terms of the received signals; that is, solve for a and b in the set of linear equations:

$$r_1 = \alpha^\wedge\, a + \beta^\wedge\, (-b^*) + n_1$$

$$r_2 = \alpha^\wedge\, b + \beta^\wedge\, a^* + n_2.$$

Take the complex conjugate of the second equation and ignoring n_j to yield a set of two linear equations for the unknowns a and b*. Then solve by matrix inversion:

$$a^\wedge = (\alpha^{\wedge *}\, r_1 + \beta^\wedge\, r_2^*)/(|\alpha^\wedge|^2 + |\beta^\wedge|^2)$$

$$b^{\wedge *} = (-\beta^{\wedge *}\, r_1 + \alpha^\wedge\, r_2^*)/(|\alpha^\wedge|^2 + |\beta^\wedge|^2)$$

The complex conjugate of the second equation yields the estimate for b:

$$b^\wedge = (-\beta^\wedge\, r_1^* + \alpha^{\wedge *}\, r_2)/(|\alpha^\wedge|^2 + |\beta^\wedge|^2)$$

These estimates for a and b can be compared with the alternative approach of using the first subcarrier for data symbol a and the second subcarrier for the data symbol b in both transmitter antennas. In particular, let s_1 and s_2 be the received signals for the first and second subcarriers:

$$s_1 = \alpha^\wedge\, a + \beta^\wedge\, a + n_1\ .$$

$$s_2 = \alpha^\wedge\, b + \beta^\wedge\, b + n_2\ .$$

Thus if $\alpha^\wedge + \beta^\wedge$ is small even though $|\alpha^\wedge|^2 + |\beta^\wedge|^2$ is not small (i.e., fading from the two channels destructively interfering), s_1 and s_2 are dominated by noise n_1 and n_2, respectively. In contrast, the preferred embodiment has r_1 and r_2 dominated by n_1 and n_2 only when both $\alpha^\wedge\, a + \beta^\wedge\, (-b^*)$ and $\alpha^\wedge\, b^* + \beta^\wedge\, (a^*)$ are small, but this

implies $|\alpha^\wedge|^2 + |\beta^\wedge|^2$ is small. That is, the preferred embodiment assignment of a pair of data symbols to a pair of subcarriers can overcome fading.

3. Two antennas, pilot symbol pairing preferred embodiment

Figure 4 illustrates a preferred embodiment with pairs of pilot symbols of a burst transformed to create a second burst analogous to the prior preferred embodiment of transformed pairs of data symbols. This encoding of the pilot symbols provides more efficient channel estimation.

4. Two antennas, alternate pilot symbol preferred embodiment

Figure 5 shows a variation of pilot symbol encoding in that a pair of pilot symbols on subcarriers in a burst is split with a burst for the first antenna including one subcarrier with one pilot symbol and the other subcarrier with a 0 symbol, whereas the burst for the second antenna has the first subcarrier with a 0 symbol and the other subcarrier with the second pilot symbol.

5. Two antennas, adjacent pilot symbol pairing preferred embodiment

Figure 6 illustrates another preferred embodiment with pairs of pilot symbols of a burst to transformed to create a second burst similar to the Figure 5 preferred embodiment but with the pilot symbols assigned to adjacent subcarriers. This encoding of the pilot symbols provides more efficient channel estimation.

6. Two antennas, two bursts transformation preferred embodiment

Figure 7 shows a preferred embodiment with pairs of data symbols on the same subcarrier in a pair of bursts transformed to create a second pair of bursts for a second antenna. In this preferred embodiment the received signals for the single subcarrier for the first and second bursts are again:

$$r_1 = \alpha^\wedge a + \beta^\wedge (-b^*) + n_1$$

$$r_2 = \alpha^\wedge b + \beta^\wedge a^* + n_2.$$

where the subscript refers to the burst rather than the subcarrier. Again the equations are solved to find estimates for the data symbols a and b in terms of the channel estimates and received signals.

7. Two antennas, two bursts with pilots preferred embodiment

Figure 8 shows a preferred embodiment with pairs of pilot symbols on the same subcarrier in a pair of bursts transformed to create a second pair of bursts for a second antenna. Analogous to the preferred embodiment of Figure 7, in this preferred embodiment the received signals for the single subcarrier for the first and second bursts are again:

$$r_1 = \alpha^\wedge a + \beta^\wedge (-b^*) + n_1$$

$$r_2 = \alpha^\wedge b + \beta^\wedge a^* + n_2.$$

where the subscript refers to the burst rather than the subcarrier. Again the equations are solved to find estimates for the data symbols a and b in terms of the channel estimates and received signals.

8. Further two antenna preferred embodiments

A pair of one pilot symbol and one data symbol can be used in any of the foregoing preferred embodiments; for example, Figure 9 illustrates a pilot and adjacent data symbol plus the transformed pair.

Further, non-adjacent pairs of bursts could be used in the Figures 7-8 preferred embodiments, and the mixed data-pilot symbols could also be used in versions of these preferred embodiments. For example, Figure 12 combines the pilots of Figure 5 with the data of Figure 10, and Figure 13 combines the pilots of Figure 6 with the data across bursts of Figure 7.

9. Higher order antenna preferred embodiments

Larger sets of antennas could be used for transmission and corresponding sets of symbols can be transformed in distinct ways to form a multiple bursts for transmission; this extends the pairs of symbols for two antennas. In particular, with four antennas, the data symbols on four subcarriers can be transformed with

the resulting 4 by 4 channel estimate coefficient matrix as a positive matrix to solve for the data symbols in terms of the four subcarrier received signals. Similarly, with groups of four symbols, the transformation can involve interchange among four distinct bursts.

10. Modifications

The preferred embodiments may be varied while retaining the feature of a transformed set of symbols transmitted on a other antennas for space-frequency diversity.

For example, a channel estimate could be obtained with initial or periodic bursts of all pilot symbols. A separate pilot channel may be available for channel estimates. The burst sizes and the numbers of and mixture of pilot symbols, data symbols, and zero power subcarriers may be varied, and so forth. Indeed, the following are convenient mixtures of numbers of pilot and data symbols per burst:

N=128, Npilot = 16, Ndata=90
N=256, Npilot = 16, Ndata=198
N=256, Npilot = 32, Ndata=180
N=512, Npilot = 32, Ndata=432
N=512, Npilot = 64, Ndata=396
N=1024, Npilot=64, Ndata=864
N=1024, Npilot=128, Ndata=792

Also, not all of the subcarrier symbols (pilot and data) in a burst need to be paired up and transformed for the second antenna transmission. That is, some subcarrier symbols may be paired, (a_i, b_i), and transformed to $(-b_i^*, a_i^*)$ for the second antenna transmission, but other subcarrier symbols, (a_k, b_k), not transformed and simply repeated as (a_k, b_k) for the corresponding subcarriers in the second antenna transmission.